

Type Ia supernovae in dense circumstellar gas

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We propose a simple model for the bolometric light curve of type Ia supernova exploding in a dense circumstellar (CS) envelope to describe the light curves of supernovae 2002ic and 1997cy. The modeling shows that at the radius $\sim 7 \times 10^{15}$ cm the density of CS envelopes around both supernovae is similar. The mass of the CS envelope around SN 1997cy is close to $5 M_{\odot}$, while the characteristic time of the ejection of this envelope does not exceed 600 yr. We analyze two possible evolutionary scenarios which might lead to the explosion of type Ia supernova inside a dense CS envelope: accretion on CO white dwarf in the symbiotic binary and evolution of a single star with the initial mass of about $8 M_{\odot}$. If the conjecture about the explosion of type Ia supernova in a dense CS envelope is correct in the case of SN 2002ic and SN 1997cy then the rapid loss of the red supergiant envelope and the subsequent explosion of the CO white dwarf are synchronized by certain mechanism. This mechanism might be related to the contraction of the white dwarf as it approaches the Chandrasekhar limit. We show that formation of a (super)Chandrasekhar mass due to the merger of a CO white dwarf and CO core of a red supergiant with consequent explosion is unlikely, since it does not provide the required synchronization of the rapid mass loss and explosion.

1 Introduction

Recently Hamuy et al. (2003) upon the basis of the spectra and light curve of the supernova SN 2002ic with narrow H α emission suggested that this object was a SN Ia interacting with a dense circumstellar (CS) envelope. Furthermore, Hamuy et al. claim that another supernova, SN 1997cy, classified as SN IIn (i.e., the supernova with narrow H α emission) is a counterpart of SN 2002ic. The narrow unresolved H α line is attributed to the emission of the photoionized dense CS gas, while H α broad component with the full width at half maximum of $\approx 1800 \text{ km s}^{-1}$ is identified with the emission of shocked dense CS clouds. The dense CS matter (CSM) according to Hamuy et al. (2003) is associated with a high mass-loss from the red supergiant. The latter may be either a companion to a white dwarf in a symbiotic binary system, or a presupernova itself, if supernova originates from a single intermediate mass star in the SN 1.5 scenario (Iben and Renzini 1983).

The luminosity of SN 2002ic is high by SN Ia standards and this is attributed to the interaction with the dense CS matter (Hamuy et al. 2003). Remarkably, the light curve of SN 1997cy has been already modeled in terms of the CS interaction (Turatto et al. 2000). However, in the latter study SN 1997cy was claimed to be a hypernova with the enormous energy of 3×10^{52} erg and large mass of $25 M_{\odot}$. The hypernova model is, of course, incompatible with the hypothesis of SN Ia as it was admitted by Hamuy et al. (2003).

On the other hand, it was demonstrated recently that the hypernova model is not necessary at all to account for the bolometric light curve of SN 1997cy; the CS interaction of a normal supernova with a typical energy of 10^{51} erg and low mass of $1.5 M_{\odot}$ is quite successful in reproducing the light curve of SN 1997cy (Chugai and Danziger 2003). This result along with the spectral arguments in favor of explosion of SN Ia in the case of SN 1997cy (Hamuy et al. 2003) compels us to consider the explosion of SN Ia inside a dense CS envelope as a promising interpretation of SN 2002ic and SN 1997cy.

Despite it is not clear as yet how the spectrum of SN Ia forms in the case of the strong CS interaction, it would be sensible to study the density and the structure of the CS envelope using constraints imposed by the bolometric light curve. Here we model the light curves of both aforementioned supernovae assuming that their radiation is a combination of the radioactive luminosity of SN Ia and the luminosity powered by the interaction of the supernova with the dense CS environment. The results are discussed then in terms of different evolutionary scenarios presumably leading to SN 2002ic and SN 1997cy events.

2 The light curve model

Let us assume that SN Ia explodes inside a spherically-symmetric CS envelope. We are interested in the bolometric light curve produced by the superposition of the intrinsic radioactive luminosity of SN Ia and of the luminosity powered by the interaction with the CS matter. To compute the light curve we use the model which was applied for the modeling of the light curve of SN 1998S (Chugai 2001). In this model the interaction dynamics is calculated in the thin shell approximation which treats the region between the forward and reverse shock waves as infinitely thin shell (Chevalier 1982). The supernova envelope is characterized by the mass (M), kinetic energy (E), and presupernova radius (R_0). We assume that the initial kinematics of the supernova envelope is free expansion ($v \propto r$) and the density distribution in this envelope is exponential, $\rho \propto \exp(-v/v_0)$, where v_0 is defined by E and M . Below we adopt $M = 1.4 M_\odot$, $E = 1.5 \times 10^{51}$ erg, and the ^{56}Ni mass of $0.7 M_\odot$. This choice is consistent with SN Ia delayed detonation models with maximal ^{56}Ni mass (Höflich et al. 1995).

The numerical solution of the equation of motion for the thin shell provides us with the evolution of the shell radius and velocity. The resulting kinetic luminosities of the forward and reverse shock waves are transformed into X-ray luminosities using cooling rates of the post-shock gas (Chugai 1992). The X-ray radiation of both shocks with corresponding temperatures is partially absorbed by the supernova envelope, thin shell and the CS gas. The bolometric luminosity powered by the interaction we calculate as the total absorbed X-ray luminosity. This simple model ignores details of the optical spectrum formation and cannot describe the emergent spectrum in detail.

The light curve powered by the radioactive decay $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ is calculated using analytical theory for homogeneous envelope (Arnett 1980). To compute the overall energy deposition rate we assume that ^{56}Ni is mixed in the inner $0.8 M_\odot$. The interaction of gamma-rays with the matter is treated in the single flight approximation assuming the absorption coefficient of $0.03 \text{ cm}^2 \text{ g}^{-1}$. The opacity is assumed to be $0.15 \text{ cm}^2 \text{ g}^{-1}$.

The calculated bolometric curves of SN Ia without and with the CS interaction assuming the wind with a constant mass loss rate ($\rho \propto r^{-2}$) are shown in Fig. 1. The density parameter $w = 4\pi r^2 \rho$ for the models in Fig. 1 is $4 \times 10^{15} \text{ g cm}^{-1}$, $2 \times 10^{16} \text{ g cm}^{-1}$, and $10^{17} \text{ g cm}^{-1}$, respectively. For the wind velocity 10 km s^{-1} these values correspond to the mass loss rate $6 \times 10^{-5} M_\odot \text{ yr}^{-1}$, $3 \times 10^{-4} M_\odot \text{ yr}^{-1}$, and $1.5 \times 10^{-3} M_\odot \text{ yr}^{-1}$. Figure 1 shows that the contribution of the interaction to the SN Ia luminosity at the light maximum becomes substantial for $w > 10^{16} \text{ g cm}^{-1}$, while the contribution of the interaction with the more rarefied wind, $w \sim 10^{16} \text{ g}$

cm^{-1} can be detected only at the very late epoch ($t > 1$ yr). Amazingly, at late time ($t \sim 300$ d), the interaction luminosity for low CS density depends on w more steeply than for high CS density, i.e., there is a saturation effect. This is related to the fact that for low w the luminosity is determined primarily by the radiative reverse shock wave while the contribution of the adiabatic forward shock increases with w . For high w the forward shock wave becomes radiative and dominant, so the overall luminosity turns out to be $L \propto wv_s^3$, (where v_s is the thin shell velocity). In this case the luminosity obviously grows less rapidly than w since the velocity v_s notably decreases as w increases.

We considered above only the case of the stationary wind. However, the shape of the light curve powered by the CS interaction depends on the density distribution in the CS envelope. This fact will be taken into account below in the modeling of the light curves of SN 2002ic and SN 1997cy.

3 Light curves of SN 2002ic and SN 1997cy and their CS envelopes

The *BVI* light curves during 70 day interval are available for SN 2002ic. To recover monochromatic light curves using our bolometric light curve model one needs to specify the photosphere radius (R_p). We assume that the photosphere coincides with the thin shell, i.e, $R_p = R_s$. This equality is justified for SN 1998S (SN IIn) where the opaque thin shell forms at the SN/CSM interface (Chugai 2001). However, for SN 2002ic this assumption should be considered as a rough approximation since the spectrum does not show the smooth continuum which is characteristic of SN 1998S. Adopting $R_p = R_s$ and using the calculated bolometric luminosity we derive the effective temperature and assuming black-body spectrum we then compute absolute *BVI* magnitudes. To compare the model with observations we adopt redshift $z = 0.067$, reddening $E(B - V) = 0.073$ (Hamuy et al. 2003) and the Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The *K*-correction related to the redshift is small and was calculated assuming black-body spectrum with the temperature $T = 10000$ K. We adopt the supernova explosion date 2452585 JD.

The *BVI* light curves for SN 2002ic are calculated for a wide range of parameter variations. The general conclusion is that the stationary wind $\rho \propto r^{-2}$ (model ic2) results in the steep light drop which is inconsistent with observations. More adequate behavior is provided by the model ic1 with the flat density distribution (Fig. 2). The light curves for both models are shown in Fig. 3. Although, we focus on the modeling of *V* light curve, which possesses pre-maximum observational points, in the other bands the

agreement is also satisfactory. In the I band the accuracy of the fit for the model ic1 is better than 0.2 mag. Deviations are greatest in the B band, although the general behavior is reproduced quite sensibly. The bolometric light curves for both models are shown in Fig. 4. It demonstrates that CS interaction contributes about 50% at the light maximum and dominates after the maximum. This inference is qualitatively consistent with the decomposition of the light curve of SN 2002ic by Hamuy et al. (2003). Note, for the interaction to be prominent at the light maximum, the CS envelope must be dense at the radius $r \sim 2 \times 10^{15}$ cm. With the expansion velocity $u \sim 10$ km s $^{-1}$ the age of this matter is $\sim r/u \sim 70$ yr; i.e., the supernova must explode not later than $\sim 10^2$ yr after the termination of the major mass loss episode.

Some uncertainty in the choice of the photospheric radius may affect the derived CS density. To check the effect of this uncertainty we calculated monochromatic light curves of SN 2002ic assuming $R_p = 0.8R_s$. The best fit is obtained for the CS density 10% larger than that for the model ic1. This demonstrates that the derived CS density is not very sensitive to the assumption on the photospheric radius.

The lack of photometric data for SN 2002ic at late epoch (> 70 days) does not permit us to derive the CS density at distances exceeding $\approx 7 \times 10^{15}$ cm. Within this radius, the integrated mass of the CS envelope is $\approx 0.4 M_\odot$.

Fortunately, for SN 1997cy the light curve is traced for over 600 days after the outburst (Turatto et al. 2000). The bolometric light curve of SN 1997cy published by Turatto et al. (corrected for the adopted by us $H_0 = 70$ km s $^{-1}$ Mpc $^{-1}$) is shown in Fig. 5. In this plot we also present our simulated light curves for models cy3 and cy4 with CS density profiles shown in Fig. 6. The model cy3 has the same density distribution as the model ic1 for SN 2002ic, with the exception that the density is 10% higher in the cy3 model. The model cy4 with the inner density minimum shows the similar fit of the light curve as the model cy3 and thus demonstrates the uncertainty in the choice of the CS density distribution in the inner region. Yet we note that the CS densities around SN 1997cy and SN 2002ic are roughly similar at the radii of $\sim 7 \times 10^{15}$ cm.

The steepening of the light curve after about day 500 indicates the CS density drop at the radius $r = R_b \approx 2 \times 10^{16}$ (Figs. 5 and 6). The integrated mass of the CS envelope is $M_{cs} = 5.4 M_\odot$ for the model cy3 and $5.9 M_\odot$ for the model cy4. We adopt the "minimal" estimate $M_{cs} = 5.4 M_\odot$. The recovered CS mass for SN 1997cy is close to that found earlier in the low mass supernova model (Chugai and Danziger 2003). More surprising is that the mass of the CS envelope recovered by Turatto et al. (2000) in their model of hypernova is also practically the same ($\approx 5 M_\odot$).

The age of the dense CS envelope around SN 1997cy is $t_{cs} = R_b/u =$

630/ u_1 yr, where u_1 is the flow velocity in units of 10 km s⁻¹. The average mass loss rate is, therefore,

$$\dot{M} = M_{\text{cs}}/t_{\text{cs}} = 8 \times 10^{-3} \left(\frac{M_{\text{cs}}}{5 M_{\odot}} \right) u_1 M_{\odot} \text{ yr}^{-1}. \quad (1)$$

The velocity of the superwind is generally 10 – 20 km s⁻¹ (Wood 1993), so the average mass loss rate for the presupernova of SN 1997cy assuming CS mass 5.4 M_{\odot} is $\dot{M} \sim 10^{-2} M_{\odot} \text{ yr}^{-1}$. Remarkably, given the similar density of the CS envelope around SN 2002ic, the estimated average mass loss rate is characteristic of this event too.

Let us now check whether the derived CS density distribution around SN 1997cy is consistent with the luminosity of the narrow H α emission. The emission measure of the CS envelope in the model cy3 on day 70 is $6.4 \times 10^{65} x^2 \text{ cm}^{-3}$ (where x is the hydrogen ionization degree). Adopting the electron temperature 10⁴ K, the predicted recombination luminosity of H α in Menzel case B is $\approx 2 \times 10^{41} x^2 \text{ erg s}^{-1}$. Turatto et al. (2000) distinguish in the H α profile on day 70 three components — narrow, intermediate, and broad. However, the relative contribution of each component is not reported. To minimize uncertainty related to the broad component which is affected by the blend of Fe II lines, we consider only the intermediate component and the narrow one within the range of radial velocities $|v_r| < 2000 \text{ km s}^{-1}$. The latter is the range of the velocities of the broad H α component in SN 2002ic either (Hamuy et al. 2003). The spectrum of SN 1997cy on day 70 (Turatto et al. 2000) provides a rough luminosity estimate for these two components $L \sim 5 \times 10^{40} \text{ erg s}^{-1}$. According to the data on SN 2002ic obtained by Hamuy et al. (2003) we assume that the contributions of narrow and intermediate (i.e., broad in SN 2002ic) components are comparable. With this assumption the luminosity of the narrow component in SN 1997cy is $\sim 2.5 \times 10^{40} \text{ erg s}^{-1}$. Combined with the luminosity suggested by the emission measure, the latter luminosity implies the average ionization degree in the CS envelope $x \sim 0.35$. This suggests the Thomson optical depth of the CS envelope of $\tau_{\text{T}} \approx 0.5$.

Remarkably, the luminosity of narrow H α in SN 2002ic during whole observed period ($t \leq 70$ days) is practically constant and equal to $\approx 2 \times 10^{40} \text{ erg s}^{-1}$ (Hamuy et al. 2003). We thus conclude that the luminosity of narrow H α in both supernovae is similar at the epoch of 70 days. This fact taken together with the similarity of the CS density at $r \sim 7 \times 10^{15} \text{ cm}$ indicates that for SN 2002ic the structure of the CS envelope and its total mass are roughly similar to those of SN 1997cy. We thus expect that the mass of the CS envelope of SN 2002ic is probably also several solar mass.

4 The nature of presupernova

The striking feature of progenitors of both SN 2002ic and SN 1997cy is an unusually high mass loss rate $\dot{M} \sim 10^{-2} M_{\odot} \text{ yr}^{-1}$ during several hundred years prior to the explosion. This indicates the existence of certain mechanism that synchronizes the phase of violent mass loss with the epoch of supernova explosion. If SN 2002ic and SN 1997cy actually are SNe Ia, it is naturally to assume that the violent mass loss is related to the epoch when CO white dwarf attains the Chandrasekhar mass (M_{Ch}).

Following the hypothesis of Hamuy et al. (2003) we consider two scenarios that may, in principle, result in an explosion of a SNe Ia inside hydrogen-rich circumstellar envelope: (i) an explosion of accreting white dwarf in a binary system with a red supergiant companion to the white dwarf (Whelan and Iben 1973) and (ii) an explosion of a degenerate CO core of a single star (Arnett 1969; Iben and Renzini 1983).

4.1 Binary system

The model of binary system suggests that the CO white dwarf attains the Chandrasekhar mass as a result of accretion from a red giant or supergiant companion. Since the red supergiant mass loss rate through the superwind does not exceed $3 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ (Wood 1994), rather unusual conditions are necessary for the mass loss rate to attain $10^{-2} M_{\odot} \text{ yr}^{-1}$. The required mass loss rate, as well as synchronization of explosion with the stage of intense mass loss, could be qualitatively explained within two feasible sequences of events in a binary.

The first version exploits the steepening of the mass-radius relation for white dwarfs when approaching Chandrasekhar limit. For $M \approx M_{\text{Ch}}$ a small increase of dwarf mass is accompanied by a considerable reduction of its radius. Even more, it may happen that as a result of nuclear burning in the vicinity of the maximum of temperature, a considerable fraction of the outer layers of CO dwarf may convert into ^{22}Ne ; this also may lead to some reduction of the radius of the dwarf in several hundred years immediately before the explosion. The decrease of white dwarf radius will result in the spin-up of its rotation. The rapid rotation and enhancement of magnetic field due to the differential rotation combined with the increase of the gravitational potential at the surface of white dwarf will result in the increase of the kinetic luminosity of the wind from the innermost parts of accretion disk. We assume that, similarly to the winds from white dwarfs (Hachisu et al. 1999), the interaction of this wind with the envelope of the red supergiant may cause an intense mass loss by the latter. This effect was considered by Hachisu et al. (1999) as a mechanism for the removal of angular momentum.

We are interested here in the supergiant mass loss only.

Let the mass and radius of white dwarf be M_1 and R_1 , while those of red supergiant be M_2 and R_2 . Assuming that the velocity of white dwarf stellar wind is of the order of the escape velocity (the maximum estimate) and the velocity of gas lost by red supergiant is of the order of escape velocity as well, one gets, from the condition of the balance of energy fluxes (the regime of ablation), an estimate for the typical mass loss rate by the red supergiant:

$$\dot{m}_2 = f(q)\dot{m}_1 \left(\frac{M_1}{M_2} \right) \left(\frac{R_2}{R_1} \right), \quad (2)$$

where \dot{m}_1 is the mass loss rate via the fast wind of white dwarf, $f(q)$ is the geometrical factor calculated by Hachisu et al. (1999), and $q = M_2/M_1$. Given the estimated mass of the CS envelope we adopt $q \approx 4$. For $f(q)$ we take $f \approx 0.033$ assuming that the red giant fills its Roche lobe (Hachisu et al. 1999). Inserting these values in Eq. (2) and adopting $R_2 = 1000 R_\odot$, $R_1 = 3 \times 10^{-3} R_\odot$, and $\dot{m}_1 = 10^{-5} M_\odot \text{ yr}^{-1}$ (this value corresponds to the white dwarf accretion rate limit set by Eddington luminosity) we obtain $\dot{m}_2 \approx 10^{-2} M_\odot \text{ yr}^{-1}$. The model, thus, is able to provide the required red-giant mass loss rate. However, it should be noted that this value is obtained for rather extreme assumptions about white dwarf mass loss rate and wind velocity, and assuming 100% efficiency of the ablation mechanism.

A modification of the scenario of the rapid mass loss in the symbiotic binary with the white dwarf mass approaching M_{Ch} might be the formation of a common envelope. This might happen due to the expansion of the red supergiant envelope induced by the white dwarf wind and subsequent Roche-lobe overflow. The common envelope also could result in the loss of the envelope by the red supergiant in the time scale of several hundred years.

The drawback of mechanisms of the rapid mass loss induced by the white dwarf contraction at the mass $M \approx M_{\text{Ch}}$ is the relatively weak dependence of the kinetic luminosity of the white dwarf wind on the dwarf radius. This leaves us with a troublesome question as to why the envelope is lost at the right time and not markedly earlier.

The second version of the symbiotic star evolution suggests the formation and loss of the common envelope with the subsequent merger of the sub-Chandrasekhar CO white dwarf and the degenerate CO core of the red supergiant. The formation of a super-Chandrasekhar mass object followed by the SN Ia explosion would explain then synchronization of the violent loss of the hydrogen envelope and SN Ia event. However, this *prima facie* natural synchronization mechanism suffers from the following serious problem.

For the merger of dwarf and core due to the gravitational wave radiation to occur soon after the termination of the common envelope stage, the dwarf

– core pair has to become rather close. For the merger to occur in t_0 years, the initial semi-major axis of the dwarf – core system should be (Landau and Lifshitz 1971)

$$a = 2 \times 10^9 \left(\frac{t_0}{100 \text{ yr}} \right)^{0.25} \left(\frac{M}{M_\odot} \right)^{0.5} \left(\frac{\mu}{M_\odot} \right)^{0.25} \text{ cm}, \quad (3)$$

where M is the total mass of the system and μ is its reduced mass. For instance, for similar masses of components of $0.8 M_\odot$ and $t_0 = 100$ yr the distance between components after the common envelope stage has to be $a = 2 \times 10^9$ cm. Such a close approach is accompanied by the release of 8.6×10^{49} erg of the binding energy with 4.3×10^{49} erg deposited into envelope in the form of hydrodynamic motions. This estimate only weakly depends on the masses of the dwarf and the core. If all this energy is spent on the ejection of the envelope, then, given the low binding energy of the red giant envelope ($< 10^{48}$ erg), the kinetic energy of the circumstellar envelope should be $\sim 4 \times 10^{49}$ erg. In reality, for the mass of the CS envelope of $5 M_\odot$ and velocity of its expansion $< 300 \text{ km s}^{-1}$ (Hamuy et al. 2003), the kinetic energy of the envelope is only $< 5 \times 10^{48}$ erg, i. e., at least by an order of magnitude lower. Thus, the energy released during the spiral-in cannot be spent entirely on the ejection of the envelope. On the other hand, such a huge energy cannot be radiated away in several hundred years as well. Actually, the maximum average luminosity of a gravitationally bound red supergiant with initial mass $< 10 M_\odot$ does not exceed $10^5 L_\odot$ (Iben and Renzini 1983). Even in the case of maximum luminosity the total energy radiated away in 600 yr does not exceed 8×10^{48} erg. The rate of energy generation during the spiral-in that exceeds the rate of radiation by the hydrostatic configuration, would result in a rapid expansion of the envelope and in turn-off of the spiral-in process.

To summarize, in the stage of intense mass loss from the common envelope the dwarf and the core cannot get closer that it is allowed by the energy loss via radiation and mass loss ($\sim 10^{49}$ erg). In this case the minimum final separation of the objects after common envelope phase has to be $\sim 10^{10}$ cm with unacceptably large merger time $\sim 6 \times 10^4$ yr. Thus, the model of the merger in the common envelope cannot explain synchronization of violent mass loss and supernova explosion within several hundred years. Therefore, the merger scenario for SN 2002is and SN 1997cy is unlikely.

The model of the white dwarf explosion in the system with a red supergiant component predicts an interesting effect. If the hydrogen-rich envelope of the giant is not lost completely prior to the explosion, several tenths of solar mass will then be lost due to the interaction of the supernova envelope and red supergiant. The major fraction of this matter acquires low velocity ($\sim 10^3 \text{ km s}^{-1}$) and thus should reside in the inner part of the expanding

supernova envelope (Chugai 1986; Livne et al. 1992). Detection of a narrow $H\alpha$ -line from the “inner” hydrogen in the spectrum of a SNIa would indicate an explosion in a system with red supergiant. Of course, the presence of a narrow $H\alpha$ -line from circumstellar gas strongly reduces possibility of the detection of $H\alpha$ from the central region of SNIa.

4.2 Single star

After pioneering work of Becker and Iben (1979), it is usually supposed that single stars do not form exploding CO cores of Chandrasekhar mass. For instance, Gil-Pons et al. (2003) find that stars with initial mass $(8.7 - 11)M_{\odot}$ ignite carbon in the weakly degenerate cores and the burning extends to the formation of Ne and Mg. The envelopes of stars are lost by stellar (super)wind. However, uncertainties of the models of the intermediate mass stars do not rule out completely the possibility of formation of exploding CO cores of the Chandrasekhar mass in these stars (Iben and Renzini 1983). The resulting supernovae were dubbed SN 1.5; this name has to stress their intermediate status between SNIa and SN II.

One of the uncertainties in the evolutionary computations of the limiting mass of CO cores is related to the usually ignored rotation. Dominguez et al. (1996) approximately took into account the rotation in the one-dimensional model and demonstrated that the lifting effect permits a star with the initial mass of $6.5 M_{\odot}$ to form a Chandrasekhar mass CO core.

Another obstacle to the SN 1.5-type supernovae is probably a complete loss of the envelope via superwind before the mass of the core mounts to M_{Ch} . Remarkably, in this regard, SN 1997cy exploded in a dwarf galaxy (Turatto et al. 2000), likewise, supposedly, SN 2000ic (Hamuy et al. 2003). The common property of dwarf galaxies is low metallicity that favors low mass loss rate. This might explain why the envelopes of presupernovae have not been lost by the AGB superwind prematurely.

Let the combination of low metallicity and rotation eventually result in formation of a Chandrasekhar mass CO core in a single star. What may then cause an intense mass loss by supergiant in ~ 600 yr prior to explosion? One may assume that the contraction of the core as it mounts to the Chandrasekhar mass can lead to the intense mass loss. For instance, the increase of gravitational potential and, as a consequence, the growth of temperature and density may result in a more intense energy release in the double burning shell at the core boundary. Another possibility may be related to C-burning flashes in the CO core.

The absence of smooth continuum in the early spectra of SN 2002ic implies that the mass of the hydrogen in the envelope of supernova is significantly smaller than $1 M_{\odot}$. The scenario of single star explosion thus

suggests that the hydrogen envelope should be almost completely lost prior to the explosion.

5 Conclusion

The simulations of the light curves of SN 2002ic and SN 1997cy in the model of the SN Ia expansion in a dense circumstellar envelope led us to conclusion that (i) the density of CS envelope for both supernovae is comparable and the corresponding mass loss prior to SN explosion occurred in the time scale of several hundred years with the rate of $\sim 10^{-2} M_{\odot} \text{ yr}^{-1}$; (ii) the mass of the CS envelope of SN 1997cy is close to $5 M_{\odot}$; (iii) the time scale of formation of CS envelope of SN 1997cy did not exceed 600 yr.

If SN 2002ic and SN 1997cy are actually type Ia supernovae that exploded in dense circumstellar envelopes, then there must exist a mechanism that provides the synchronization of intense outflow of a huge amount of matter in several hundred years and the SN Ia explosion event. The analysis of two scenarios of the possible evolution to the explosions of SN 2002ic and SN 1997cy – accretion onto a white dwarf in a symbiotic system or SN 1.5 scenario – does not allow us to identify with confidence the mechanism of the synchronization of the mass loss and explosion. We believe that the most natural mechanism should involve the contraction of the CO white dwarf (in the binary-star scenario) or CO core (in the SN 1.5 scenario) when approaching the Chandrasekhar limit. However, the details of the process that has to “switch-on” the violent mass loss by a supergiant several hundred years prior to the SN Ia explosion have yet to be understood. We, however, may almost certainly rule out *prima facie* conceivable scenario of the merger of CO white dwarf and CO core of a red supergiant due to the angular momentum loss via gravitational wave radiation after ejection of the common envelope.

Both scenarios have interesting predictions that may turn out crucial for their verification. The scenario of the symbiotic star predicts a wide range for the masses of CS envelopes – from several tenth of M_{\odot} to about $6 M_{\odot}$, with low masses being dominant since low-mass giants prevail in symbiotic systems. In the single star scenario the initial mass is close to $8 M_{\odot}$ and CS envelopes should be, therefore, similar and rather massive. If future observations will reveal relatively large number of SN 2002ic-type events with the mass of the CS envelope greater than one solar, then the single-star model should be preferred. At present, with only two detected SN 2002ic-like events, both indicating high-mass CS envelopes, the scenario of SN 1.5 is favored.

Note, SN 2002ic-subtype events are extremely rare. The fact that, de-

spite their luminosity exceeds the luminosity of a typical SN Ia, only two such supernovae were discovered as yet implies that their relative occurrence rate among all SNe Ia is less than 1 per cent.

This work was partially supported by Russian Foundation for Basic Research (grants 01-02-16295 and 03-02-16254) and Federal Science and Technology Program “Astronomy”.

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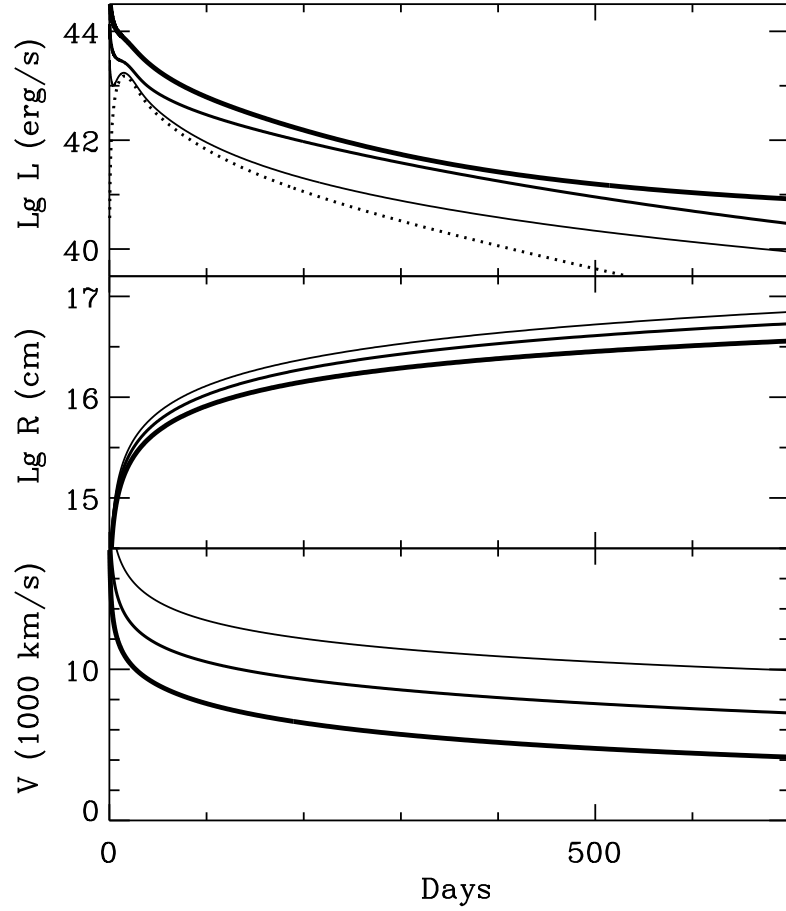


Figure 1: Bolometric light curves (upper panel), radius of the thin shell (middle panel), and its velocity (lower panel) for the model of expansion of SN Ia in the stellar wind. The light curve for SN Ia without wind is shown by dotted line. The thickness of lines (from the most thin to the most thick) corresponds to the parameter of the wind density w equal to $4 \times 10^{15} \text{ g cm}^{-3}$, $2 \times 10^{16} \text{ g cm}^{-3}$, and $10^{17} \text{ g cm}^{-3}$, respectively.

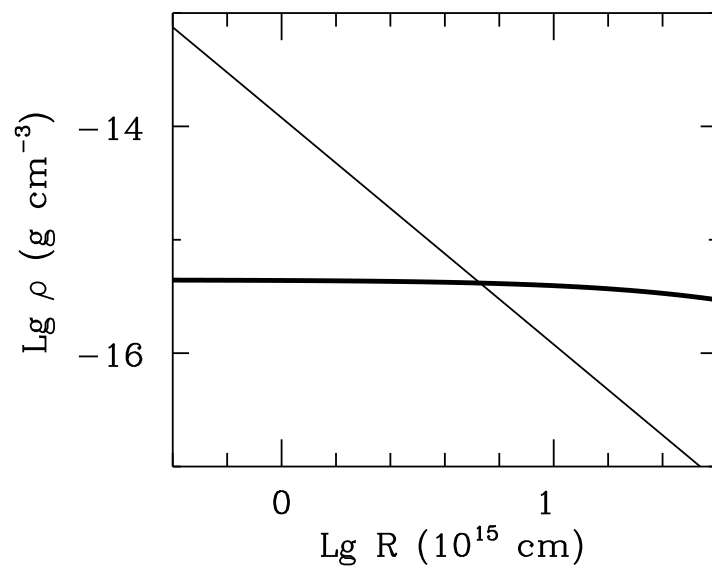


Figure 2: Density distribution in models ic1 (thick line) and ic2 (thin line).

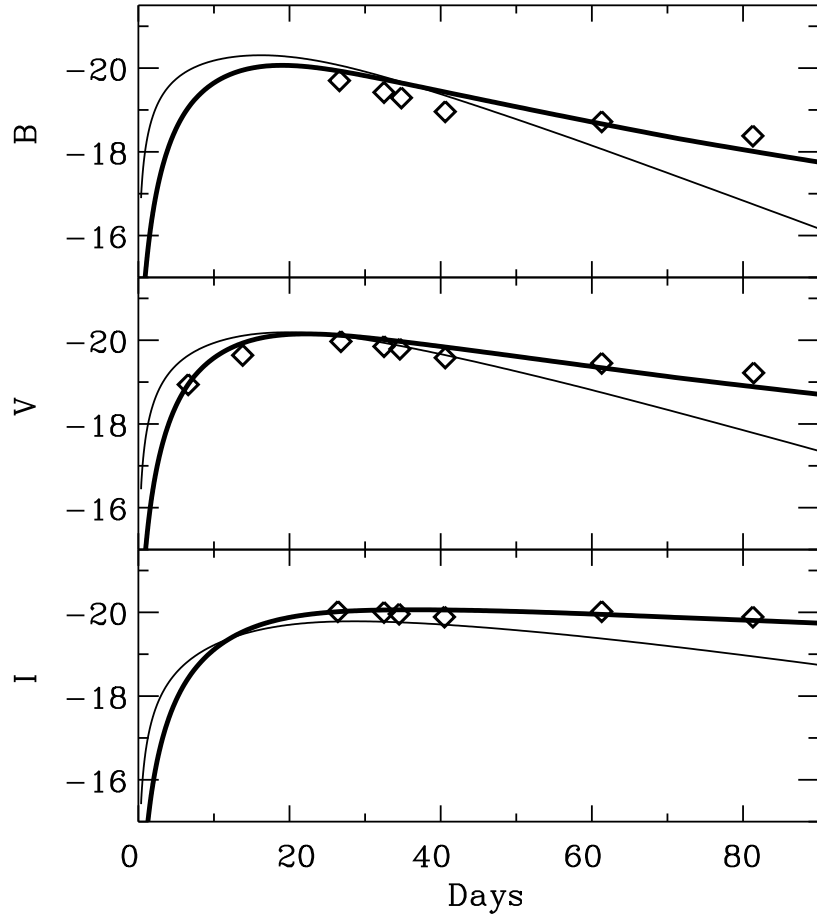


Figure 3: Light curves of SN 2002ic in BVI bands. Thick line is the model ic1, thin line is the model ic2. Observational data (Hamuy et al. 2003) is shown by diamonds.

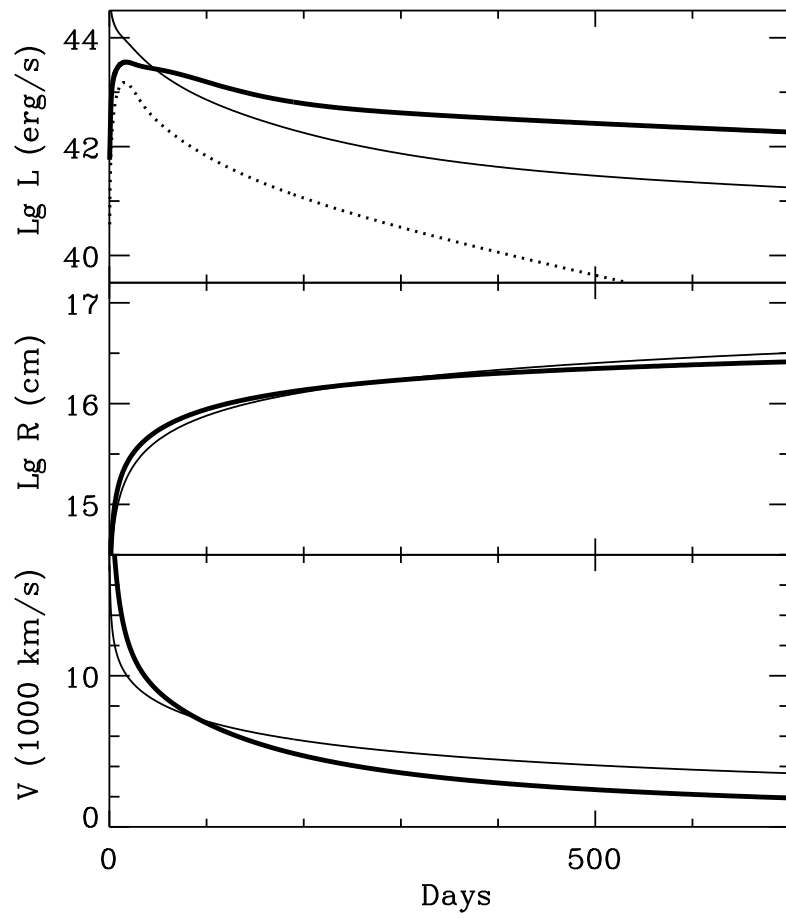


Figure 4: Bolometric light curves, radius, and velocity of the thin shell for models ic1 (thick line) and ic2 (thin line). The dotted line shows the light curve of SN Ia in the absence of CS gas.

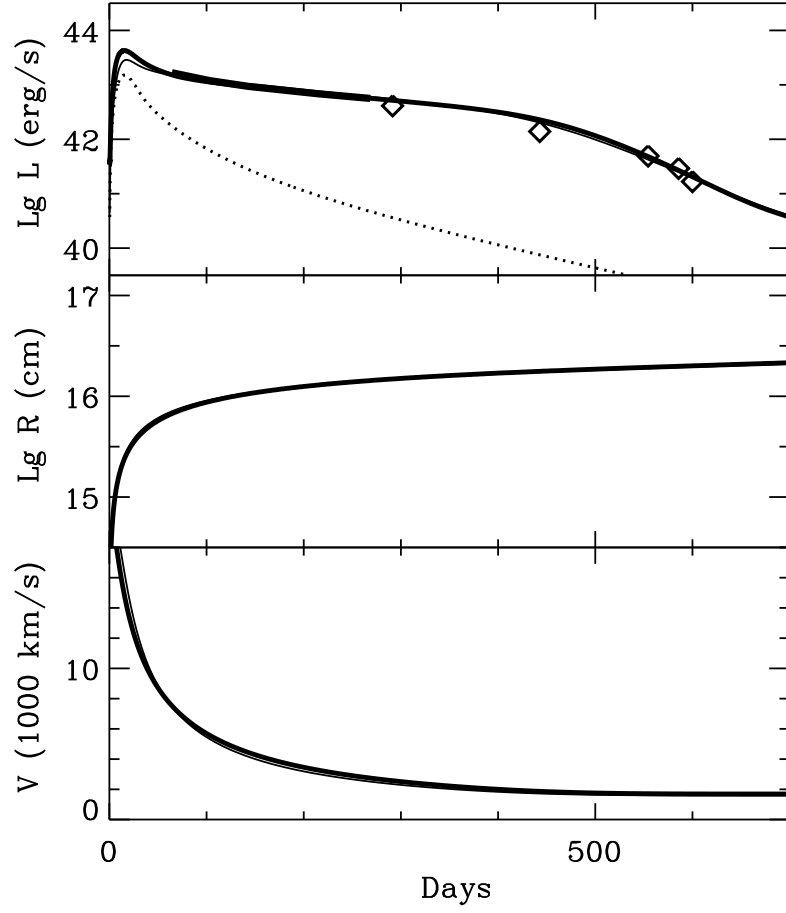


Figure 5: Bolometric light curves, radius, and velocity of the thin shell for models cy3 (thick line) and cy4 (thin line). The dashed curve shows the light curve of SN Ia without CS gas. In the upper panel the diamonds and thick line show the empirical light curve (Turatto et al. 2000) assuming $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

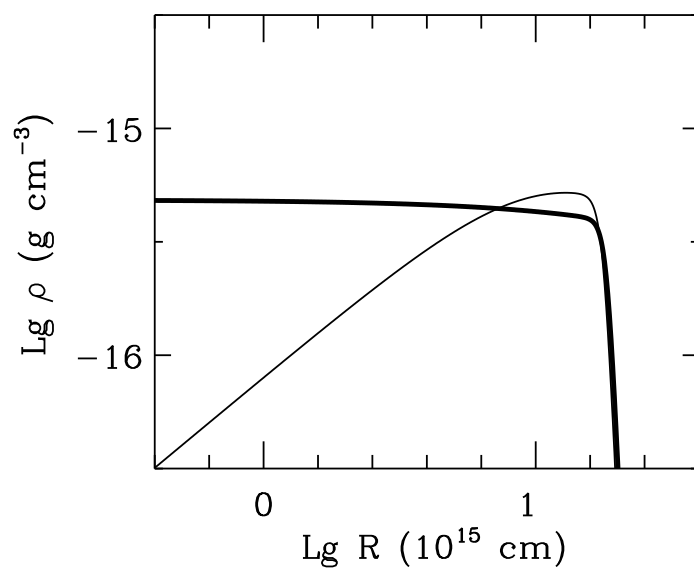


Figure 6: Density distribution in models cy3 (thick line) and cy4 (thin line).